Magnetized Target Fusion collaboration 2004: recent progress

T. Intrator for the MTF collaboration

S.Y. Zhang[1], J.H. Degnan[2], I. Furno[1],C. Grabowski[2], S.C. Hsu[1], E.L. Ruden[2], P.G. Sanchez[1], M. Tuszewski[1], W.J. Waganaar[1], G. A. Wurden[1], J Slough[3], P Park[4], D Ryutov[5], J Santarius[6]

[1]Los Alamos National Laboratory, [2]Air Force Research Laboratory, Kirtland Air Force Base, [3]Univ Washington, [4]GA, [5]LLNL, [6]Univ Wisc.

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http://fusionenergy.lanl.gov

wsx.lanl.gov

abstract

Magnetized Target Fusion (MTF) may be a low cost path to fusion, in a regime that is very different from, and intermediate between, magnetic and inertial fusion energy. It requires compression of a magnetized target plasma and consequent heating to fusion relevant conditions inside a converging flux conserver. To demonstrate the physics basis for MTF, a Field Reversed Configuration (FRC) target plasma has been chosen that will be translated axially to a region where it can be compressed. We show recent and improved FRC formation data, example deformable liner implosions, and a conceptual design for the upcoming translation experiments. We also describe a multi institution collaboration and some physics based estimates of the plasma behavior for this and other compression approaches. Our experimental research focuses on demonstrating MTF with the FRC, but many scientific issues lie on this path. The FRC is an elongated, self-organized compact toroid equilibrium that is extreme among magnetic configurations, apparently relaxed to a non force free state. There is high plasma $\beta \sim 1$, small toroidal field, probably cross-field diamagnetic current and flows, vanishing rotational transform, magnetic shear, helicity and anomalously large resistivity. Related fundamental plasma physics questions extend beyond MHD models, and are relevant to geophysical and astrophysical phenomena.

outline

- Magnetized Target Fusion (MTF): many pulsed approaches to fusion
- Physics & engineering issues
- Community with collaborations
- FRC as a plasma target for compression
- FRC results at LANL
- Summary & list of related presentations

magneto-inertial fusion

- Pulsed, high pressure approaches to fusion
- Inertial + magnetic confinement
- Magnetic field plays essential role
- Magnetized Target Fusion - MTF examples
  - Pulsed high density FRC
  - Plasma jet compression of target
  - Field reversed configuration (FRC) in a beer can

MTF physics & engineering issues

- Keep devices, coils, hardware simple
- advantages vs disadvantages of pulsed scenarios?
- How much gain is sufficient?
- Schemes, technologies for plasma compression
- Physics with large β, flow, density, collisionality
- Stability of target plasma
- Standoff drivers
- Transport, confinement of target
- Optimize target formation, design & build translation

community wide collaboration

- Attack physics & engineering issues; wide variety of approaches within MTF
  - AFRL Kirtland: Degnan - imploding flux conservers
  - LLNL: Ryutov - edge-wall xport, stability; standoff
  - Univ Wash:
    - Slough - optimize FRXL formation
    - Hoffman - FRC
  - U Wisc: Santarius - plasma jet compression
  - U Nevada Reno: Siemon - wall confinement, z-pinch
  - GA: Parks -standoff drivers, FRC concepts

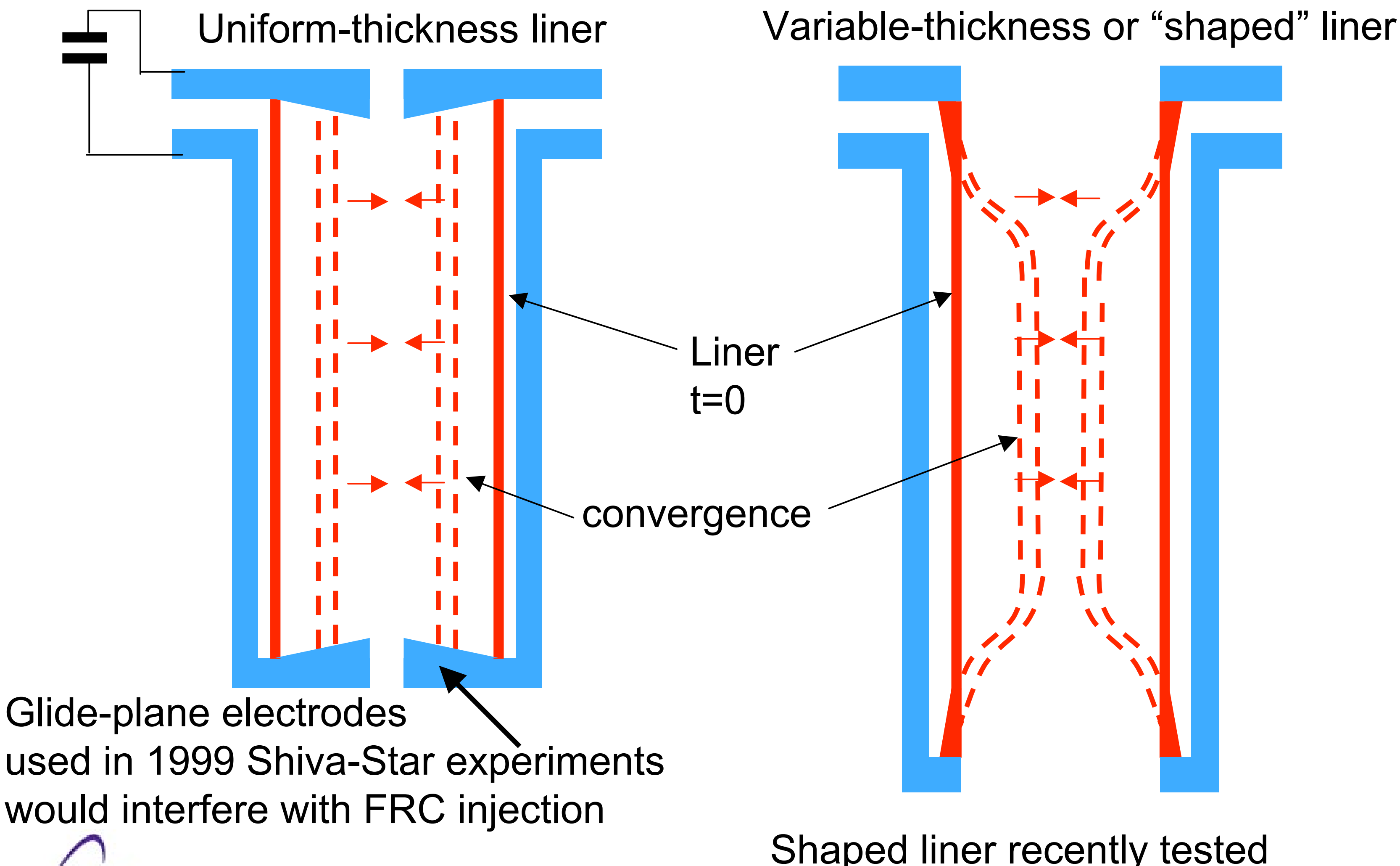
Converging flux conserver : critical technology for MTF

- Liner = radially imploding cylinder = flux conserver
- Deformable liner
  - Keep the large holes at the ends => ease FRC entry
  - Implode center section
  - Avoid sliding contacts at the ends
  - Reduce impurities
  - Better diagnostic access
  - Two approaches
    - *Z-pinch: axial current*
    - *Theta pinch: inductive, non contact drive*

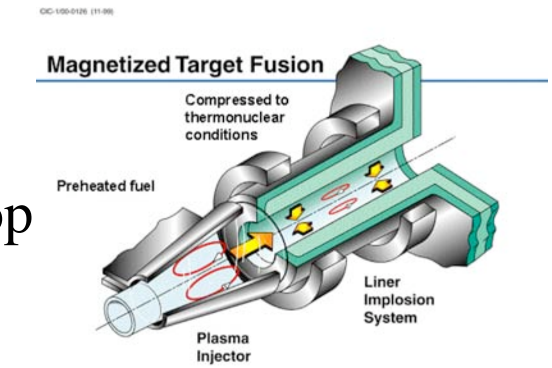
Connecting current to the liner

Z-pinch drive

AFRL Kirtland: Degnan



Magnetized Target Fusion (FRC)

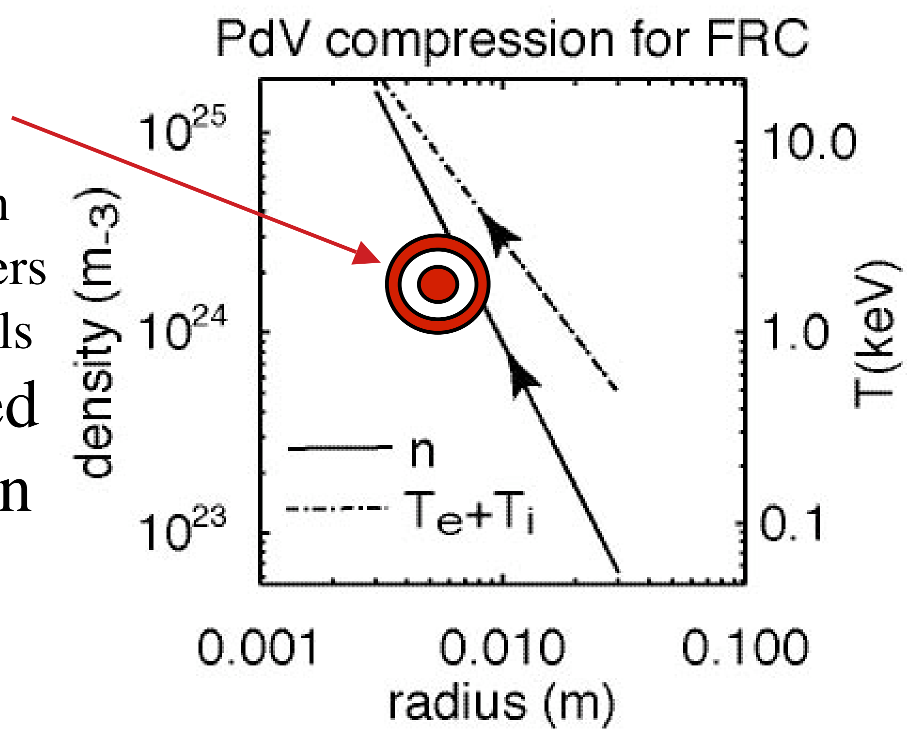


This is a fusion concept where:

- Plasma beta ranges from 0.8 to 1
- The heart of the device fits on a modest table-top
- Plasma density is high ~10^{19} cm^{-3}
- Current density can be 1000 MA/m^2
- Magnetic confining field is 500 Tesla !
- Auxiliary heating power ~ 1000 Gigawatts !
- Heating is "slow" adiabatic compression
- Initial physics research with existing facilities, technology
- Each pulse, in a reactor, has a fresh liquid first wall
- repetition rate is ~ 0.1 Hertz, i.e. there is time to clear the chamber from the previous event

MTF: compress a magnetized target

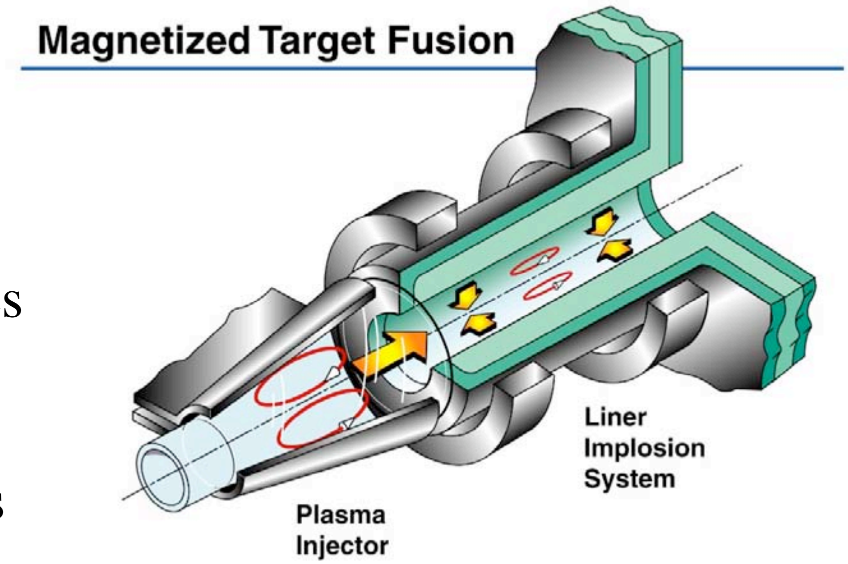
- MTF uses flux conserving compression
  - metal liners $J_z x B_\theta$ driven
  - gaseous or plasma pushers
  - compressible liquid shells
- PdV heat a magnetized target plasma to fusion conditions
  - spheromak
  - field-reversed-configuration (FRC)



Operation between MFE and IFE regimes

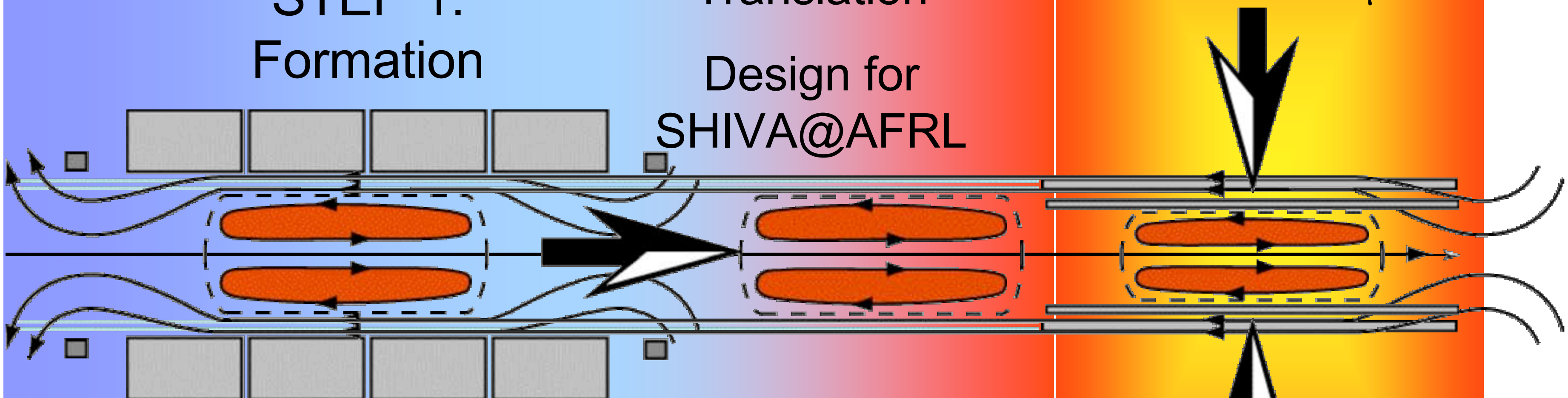
- MTF plasma regime ($n \sim 10^{19}$-10^{20} cm^{-3}, $T \sim 5$ keV)
  - Densities lie between magnetic fusion energy (MFE) and inertial fusion energy (IFE)ranges

- Advantages
  - Fusion reactivity scales as density squared >> conventional MFE.
  - Magnetic insulation reduces power compared to ICF
  - High energy efficiency
  - Pulsed-power requirements using existing facilities.



FRX-L Project: present and future

High density FRC's



FRC Goal Parameters:

- density $n \sim 10^{17}\ \mathrm{cm}^{-3}$
- temperature $T_{total} \sim 500\ eV$
- lifetime $\tau_E > 10\ \mu s$

Present funded scope 4 years

End of 4 years

FRX+L

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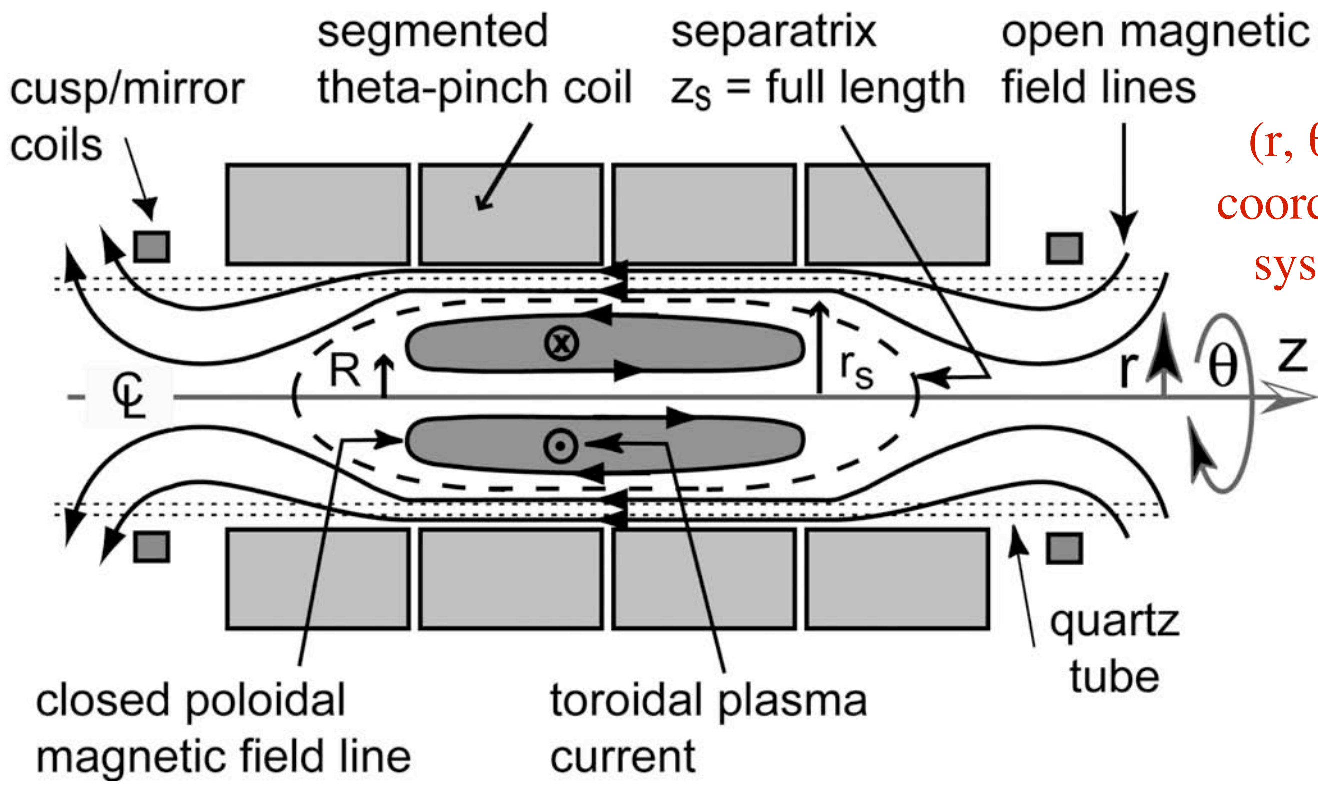
geometry & model of FRC



(r, θ, z)
coordinate
system

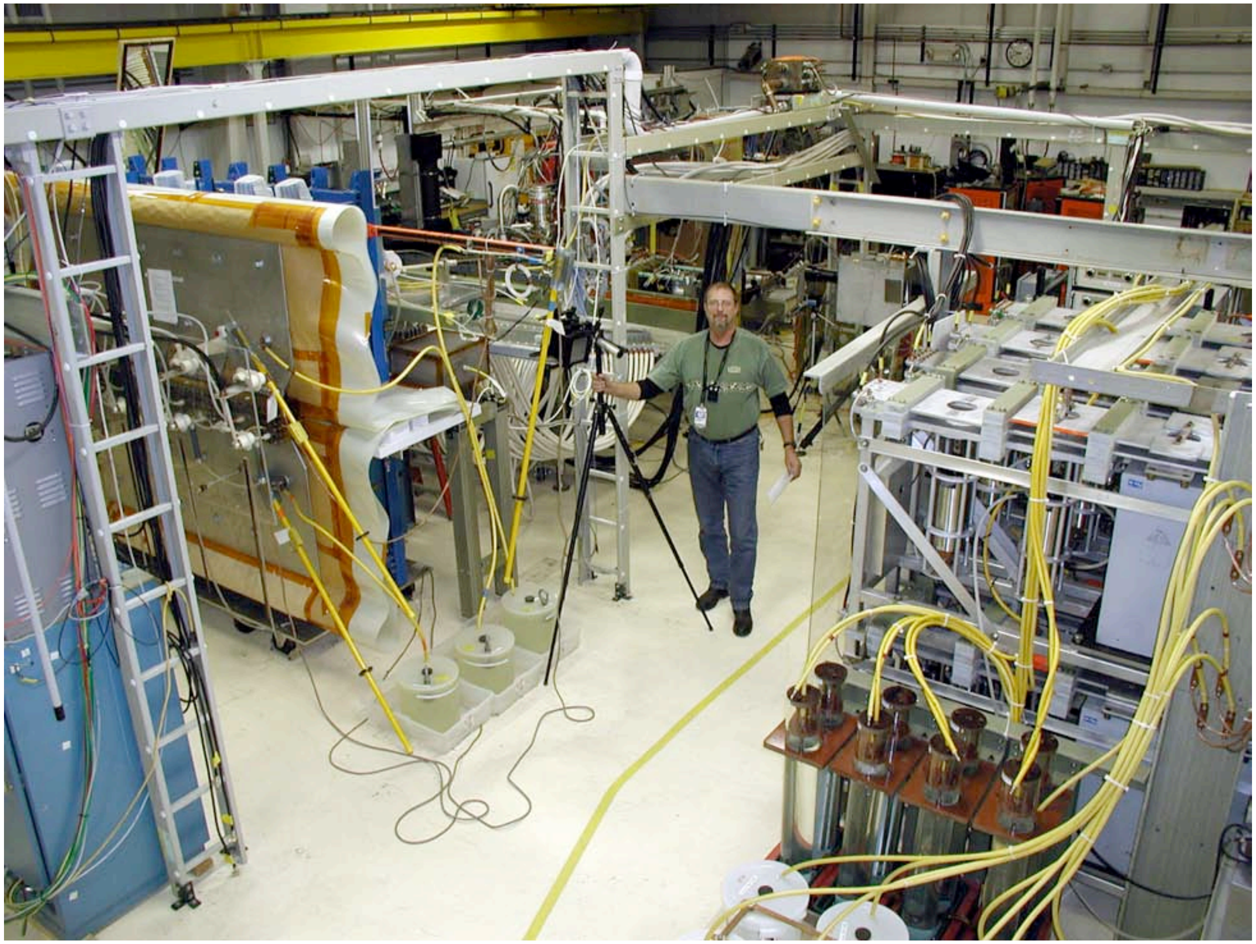
- Excluded flux radius r_s≈3cm at last closed flux surface
- Field null radius R≈2cm, separatrix length z_s≈30cm
- J•B ≈ 0, *i.e.* ***not*** a Taylor relaxed equilbrium

FRC is a good target for MTF

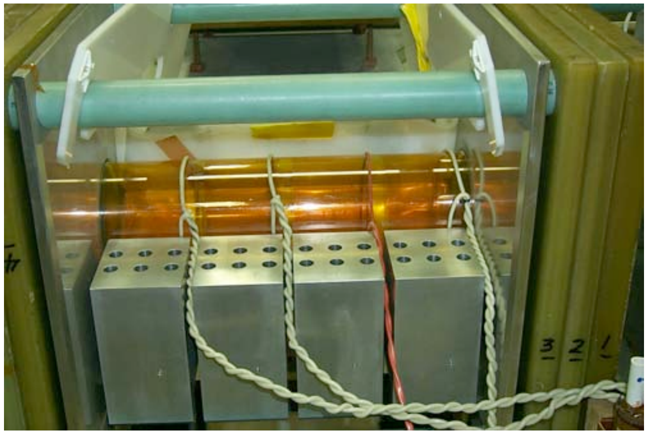
- Robust magnetic equilibrium during compression
  - Survives translation, bounce, shock heating, compression
    - Because of equilibrium + field line tension, radial compression contracts FRC axially, 2.4D compression
    - Stability properties are ≈ constant during compression
  - Natural divertor, particle exhaust, direct energy conversion

    …
- high density FRC has advantages
  - Fusion reactivity increases as n^2
  - pulsed FRC is easy path to high energy density=> high fusion reactivity

FRX-L Experimental Bay at LANL

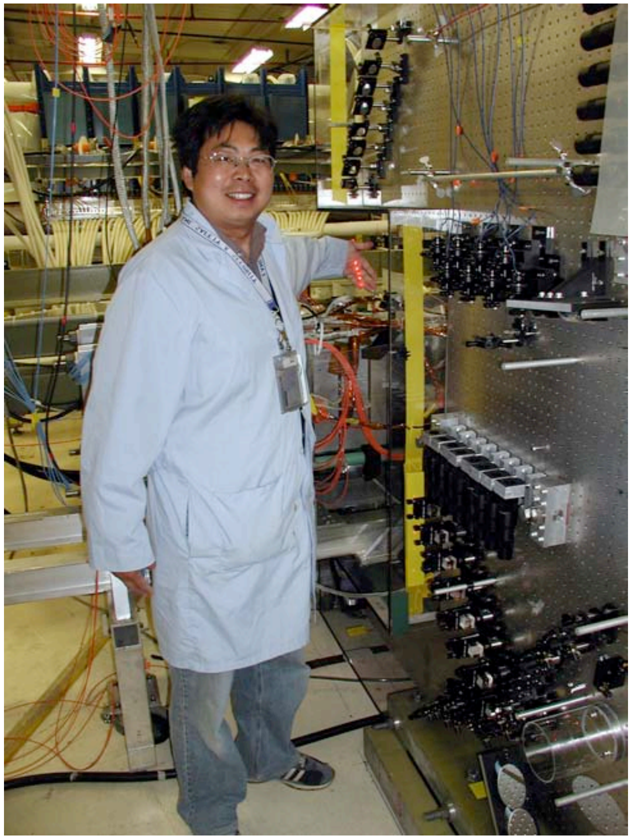


FRX-L theta coil & Diagnostics



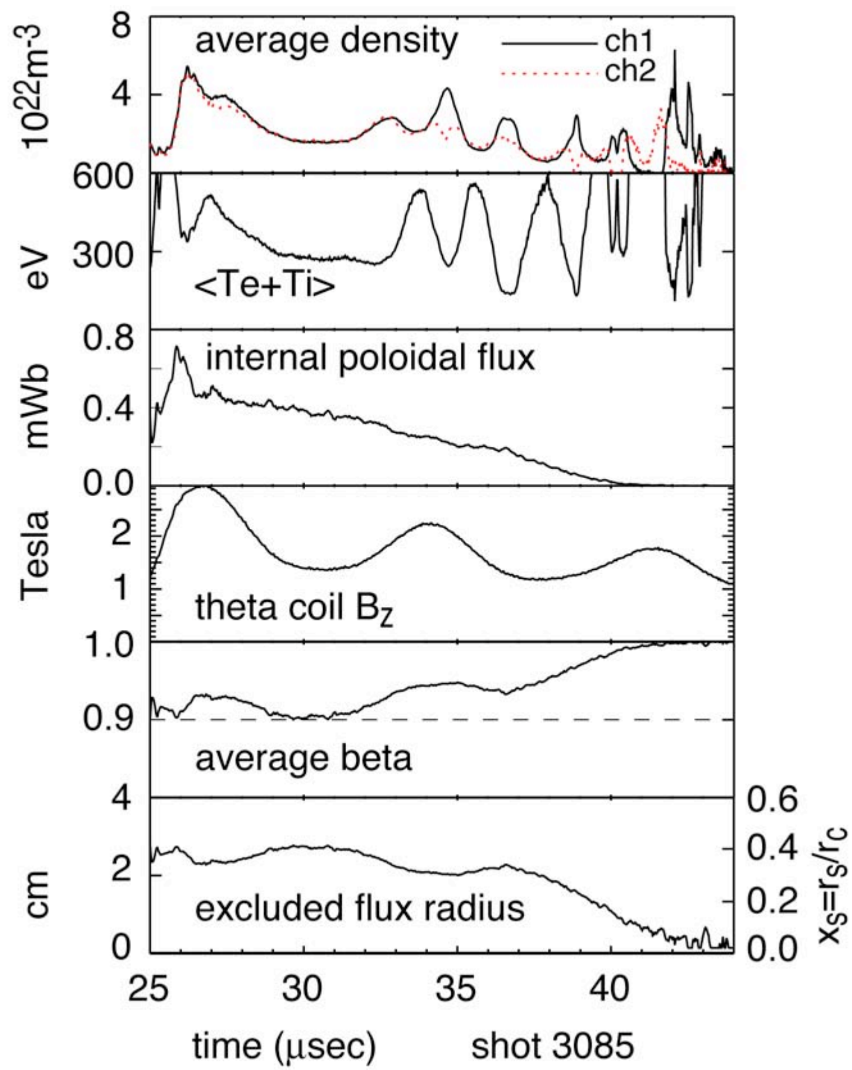
Half FRX-L theta coil,
flux loops

8-chord laser interferometer beams, vertical view through slotted theta-coil



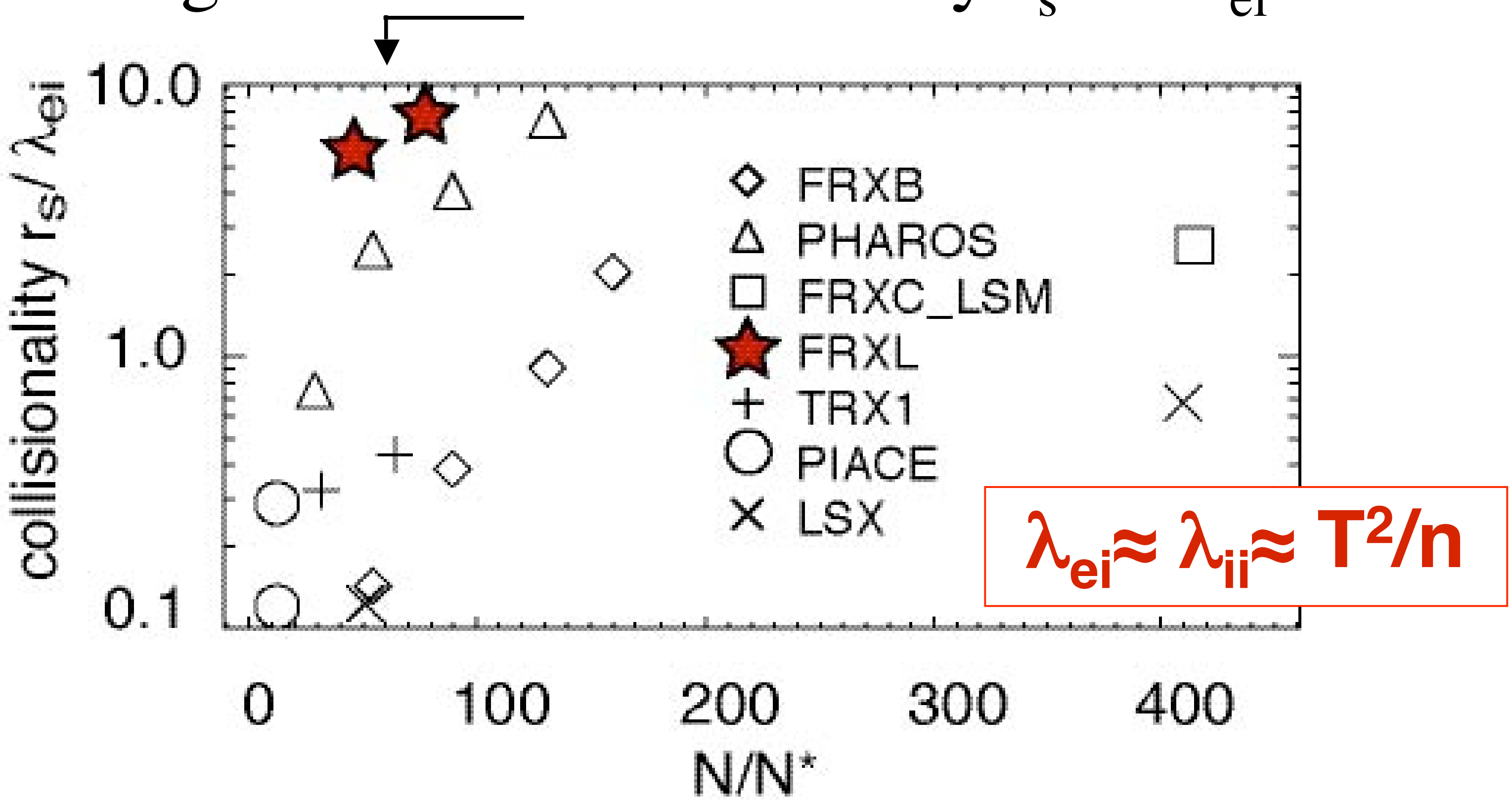
FRX-L FRC recent 2004 data

- **Increase**
  - Lifetime $\tau_{\Phi} \approx 10\ \mu sec$
  - Density $n \approx 2\text{-}3 \times 10^{22} m^{-3}$
  - temperature $T_e + T_i \approx 300$ eV
- **Diagnostics**
  - 8-chord interferometer
  - magnetics probes
  - visible spectroscopy
  - two optical tomography side-on arrays
  - (almost) operational multi-point Thomson scattering system.



FRX-L: a highly collisional FRC

High coulomb collisionality $r_s >> \lambda_{ei}$



r_s/Coulomb mean free path vs N/N* reference line density

Collisional FRC physics

- So far, similar to conventional wisdom
  - Resistivity is anomalous, 10-20 x Spitzer, and not dominated by Coulomb collisions … published
  - Flux trapping and retention is well characterized by FRC scaling laws … show data here
- Things not investigated yet
  - Flow
  - Relaxation
  - Particle, flux loss mechanisms

Resistivity describes flux dissipation

∇xB=$\mu_0 J_\theta$= $\partial B_z/\partial r$ $\Leftrightarrow$ spatial derivative
∇xE_θ= $-\partial B/\partial t$ $\Leftrightarrow$ confinement time
$E_\theta = \eta_{eff} J_\theta + v$xB (ignore Hall term)

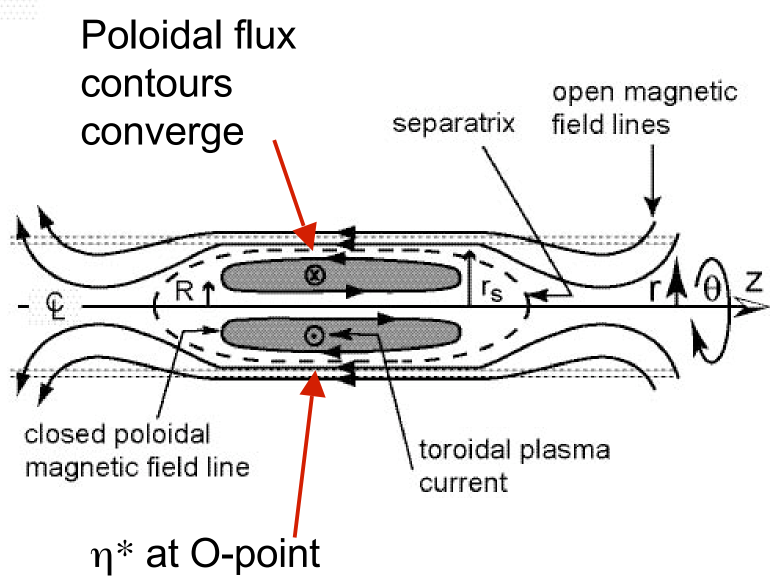
- Define the poloidal flux $\Phi_{pol} = \int_R^{rs} B_z(r)\, 2\pi\, r dr$
- Relate time history of Φ_{pol} to toroidal E_θ
  - $\int_R^r E_\theta(r)\, 2\pi\, r dr = -\partial\Phi/\partial t$
  - at the field null r=R, $E_\theta = -(\partial\Phi/\partial t)/(2\pi R)$
  - Ohm's Law => $E_\theta = (\eta/\mu_0)\partial B_z(r)/\partial r$

$$\eta(R) = -\mu_0(\partial\Phi/\partial t)/[2\pi R\, \partial B_z(r)/\partial r]$$

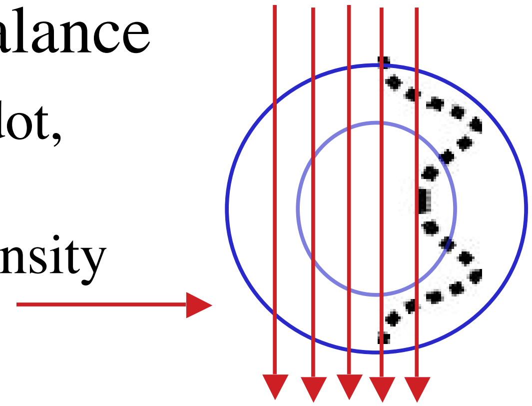
Physical picture tying global to local data

- Local resistivity requires knowledge of local $B_z(r)$
- *Resistive* like diffusion relates poloidal flux $\Phi(t)$ annihilation time scale to J_θ at the "O" point (r=R)
- Closed flux contours converge radially inward
  - η^* relates $\partial\Phi/\partial t$ to E_θ

- Total flux $\Phi(t)$ is global, inferred from outside
- edge loss model at separatrix to estimate $\eta_{sep}(\, r=r_s\,)$



Estimate resistivity at field null

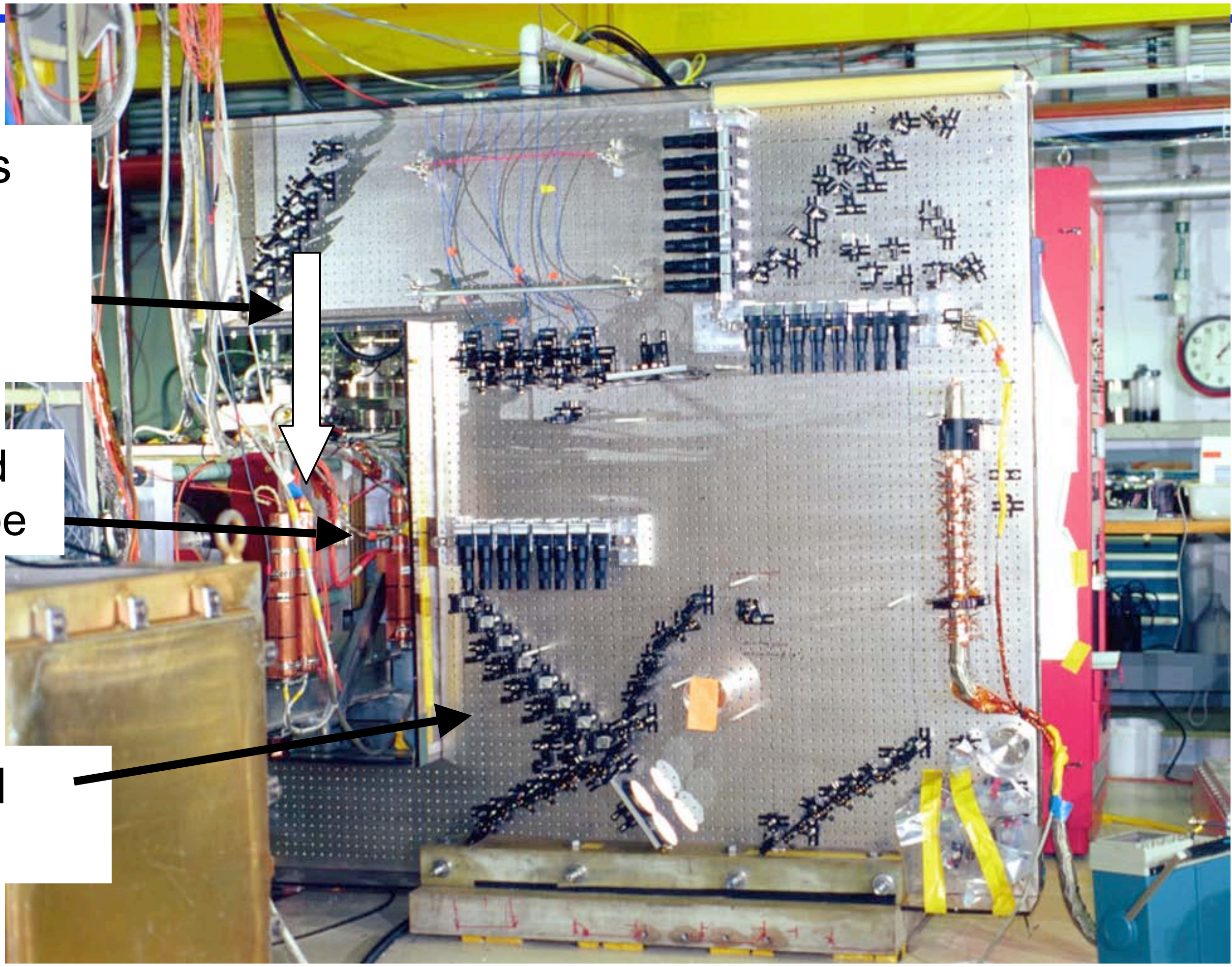


- Global quantities from pressure balance
  - Get the average $<\beta>=1-x_s^2/2$ from Bdot, flux loops, r_s
  - multichord interferometer $\Rightarrow$ local density profiles $\Rightarrow$ average density $<n>$
  - average temperature $<T>\approx <\beta>/<n>$
- interferometer data $\Rightarrow$ local $n(r)$, $\beta(r)$
  - assume flat profile $T(r)\approx<T>$ {recall $r_s\approx 2r_{Gi}$}
  - Calculate local $\beta(r) \approx n(r) <T>/(B_{ext}^2/2\mu_0)$
  - Estimate $B_z(r)/B_{ext} = 1/2\ [1- \beta(r)]^{1/2}$
  - Estimate $\partial/\partial r\ B_z(r)/B_{ext} = 1/2\ [1-\beta(r)]^{-1/2}\ d\beta(r)/dr$

At field null r=R

$$\eta_{eff}(R)/\mu_0 = -\Phi / [\tau_\Phi\ 2\pi R\ \partial B_z(r=R)/\partial r]$$

Multiple-chord interferometer - AFRL

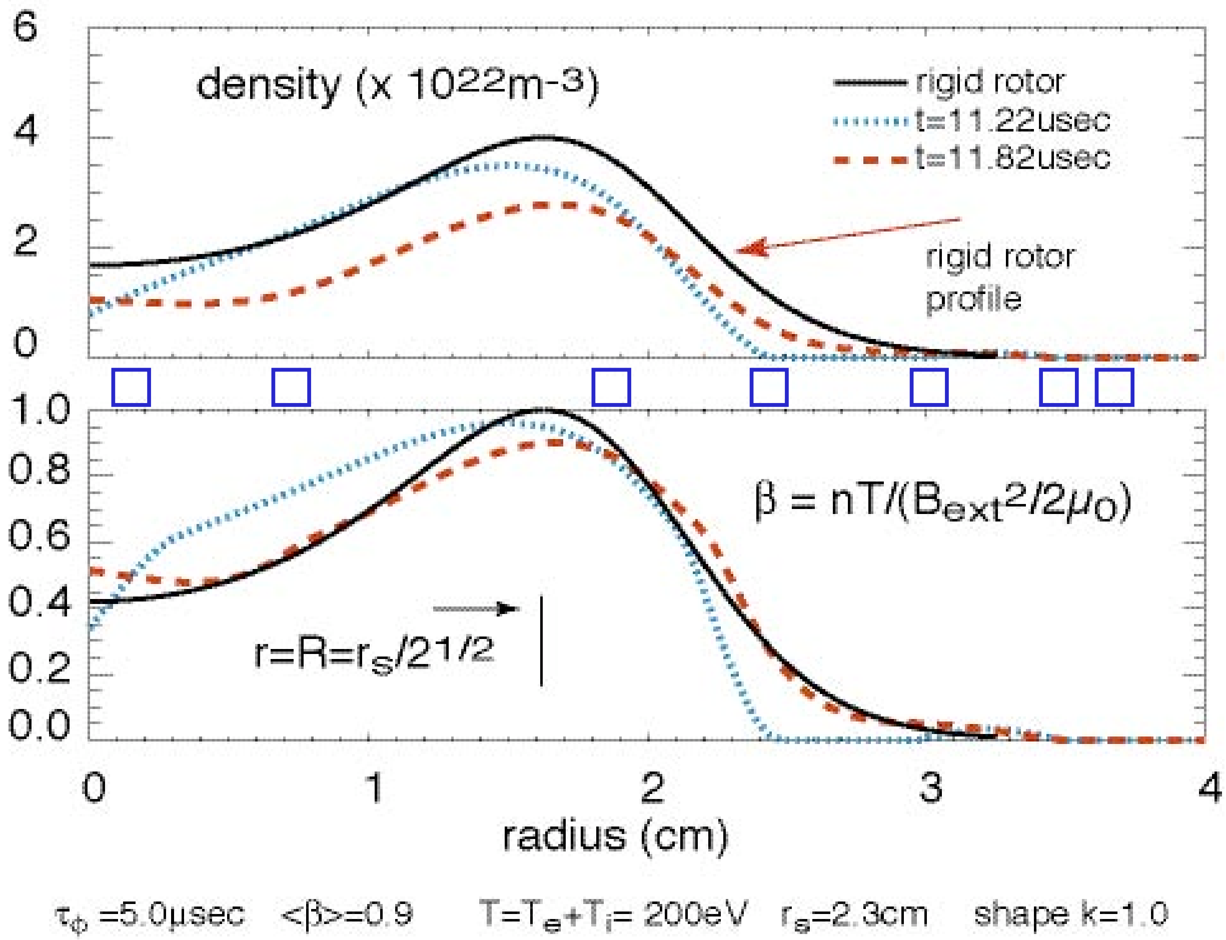


8 chords through plasma region

Coils and quartz tube

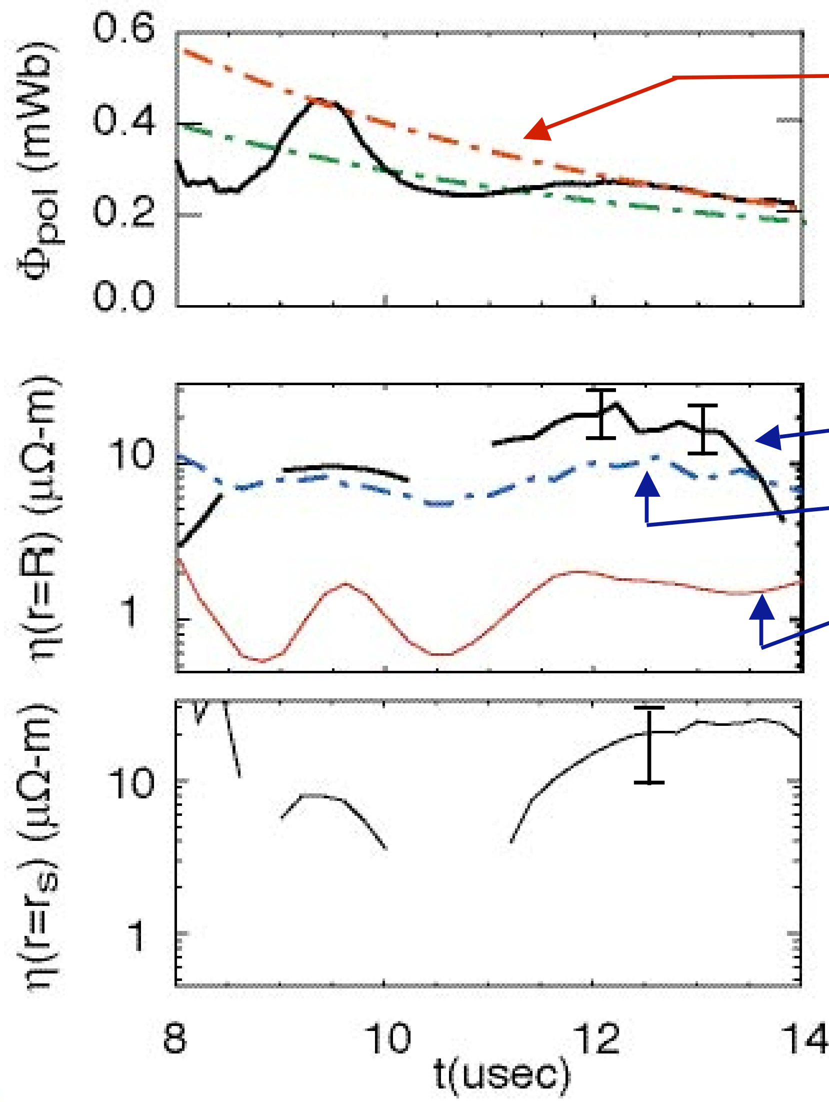
8 chord optics

Radial cuts across n(r,t) & β(r,t) reveal profiles



- Data is inverted and later compared with rigid rotor predictions
- β Gradients are less than rigid rotor profile, ie diffusivity η^*/μ_0 is larger
- □ = interferometer chord locations

Resistivity $\eta*$ at O point is large



- FRC Flux loss and exponential fits

- Estimate error bars from uncertainty in
  - Flux decay time $\tau_\phi \approx$6-8μsec
  - derivatives in β(r)

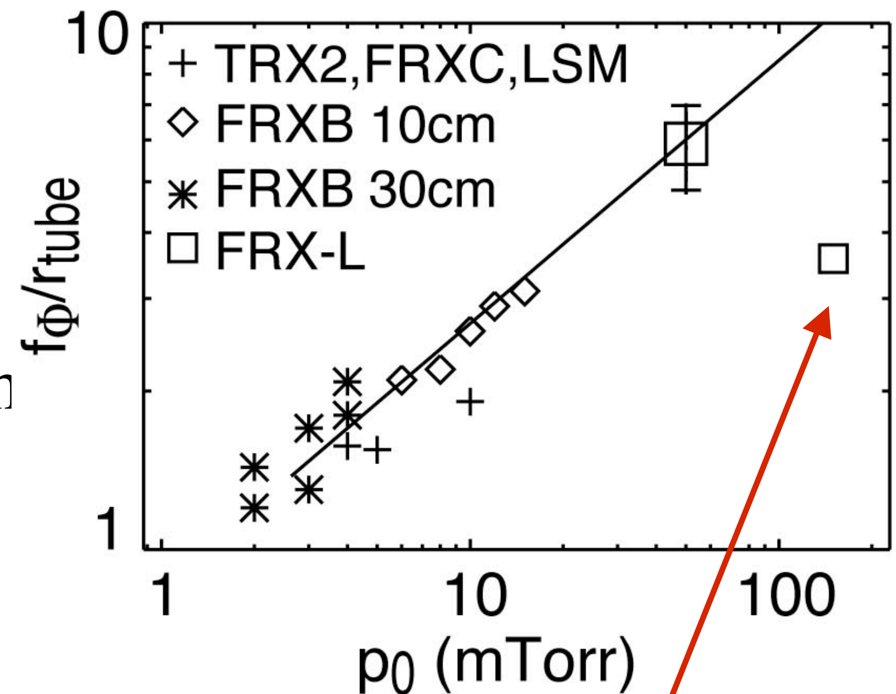
- η FRC from profile data
- $\eta*$ rigid rotor
- η Spitzer

- $\eta*$(r=R) is
  - 10-20 x classical
  - 2x rigid rotor
- $\eta*(r=R) \approx \eta*(r=r_s)$

flux retention wrt other FRC's

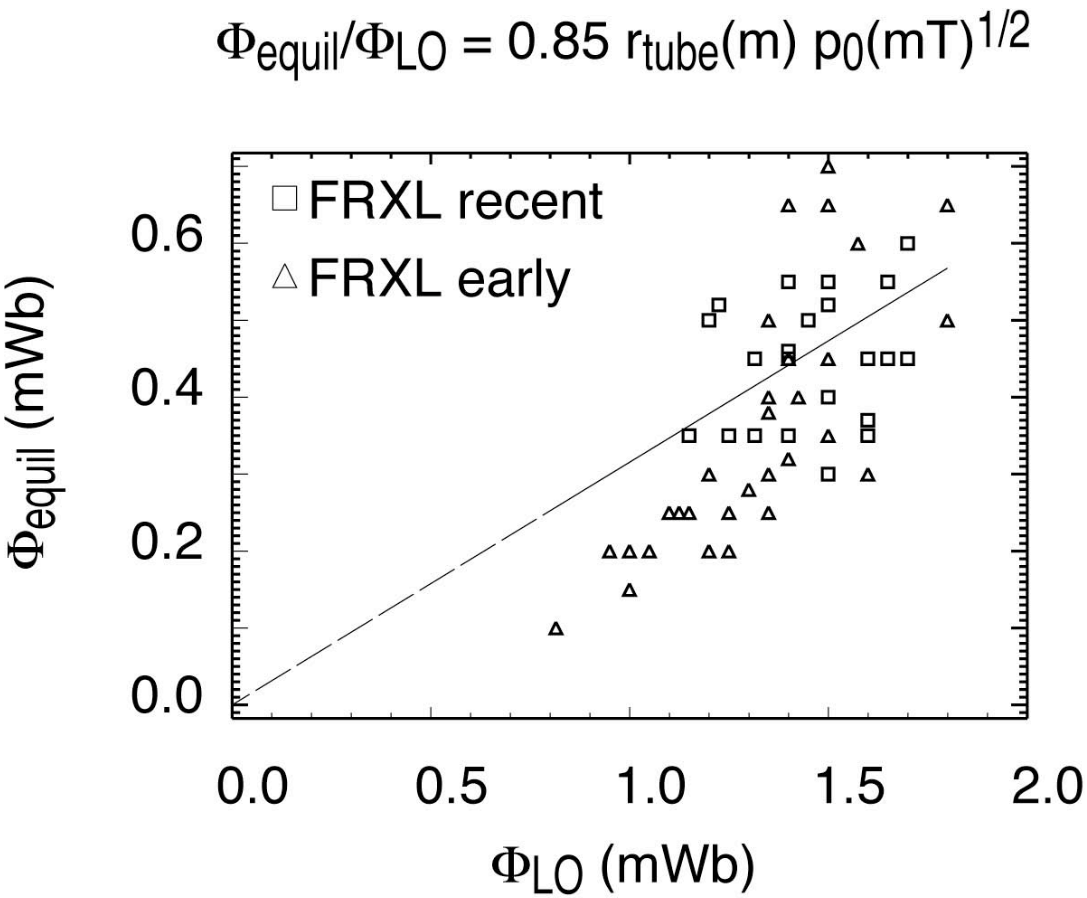
Theoretical/empirical scaling favors large devices

- $f_\Phi = 0.85 r_{wall}(m) p_0(mT)^{1/2}$
- FRXL is small, expect collisionality to change the physics eventually
- Normalized equilibrium FRC flux f_Φ/r_{wall} vs fill pressure & predictions



Very high $n>10^{17}cm^{-3}$, p_0=150mT, non optimized

trapped lift off flux Φ_{LO} => equilibrium Φ_{equil}



- Scatter plot of >100 shots
- Recent shots have better main bank timing, more bias and lift off flux

$\boxed{\Phi_{equil} \text{ scales with } \Phi_{LO}}$

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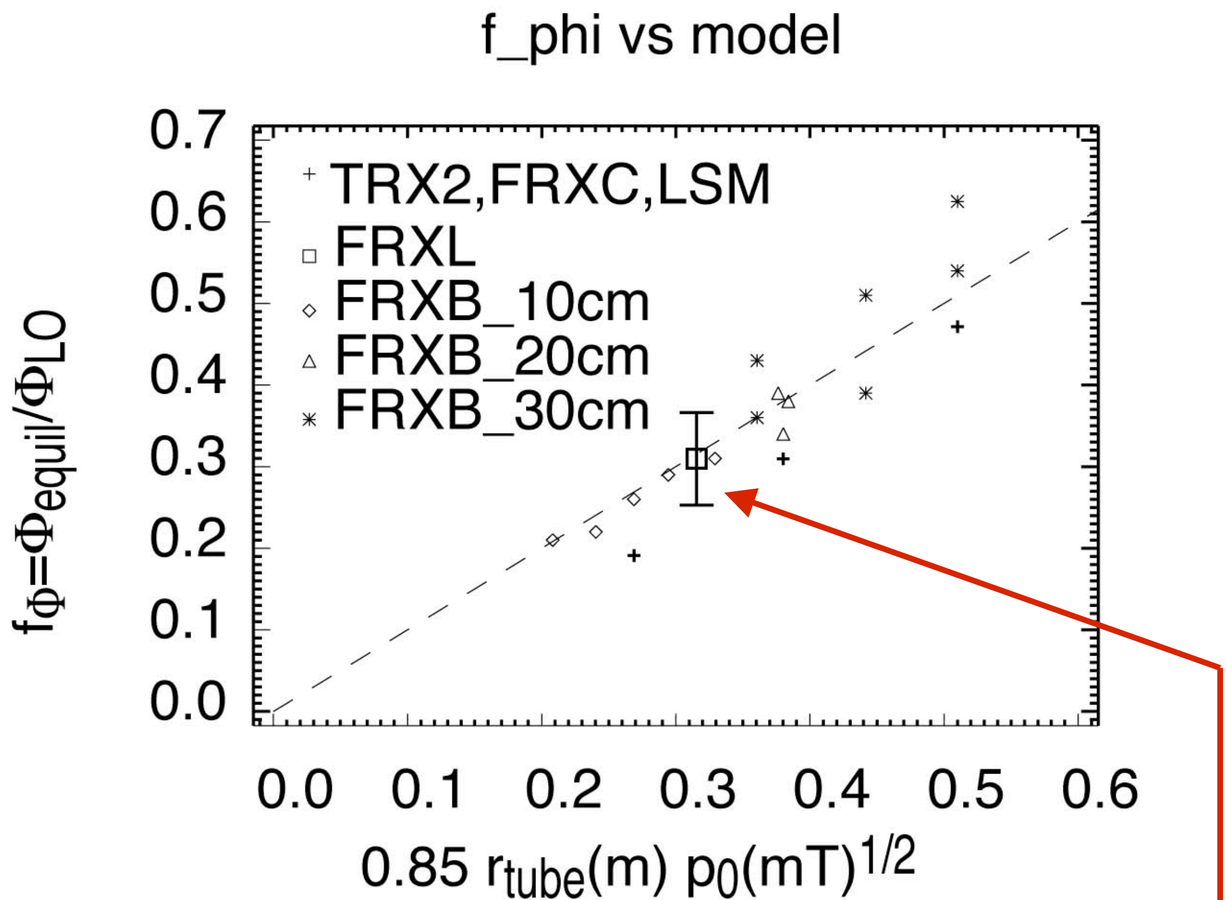
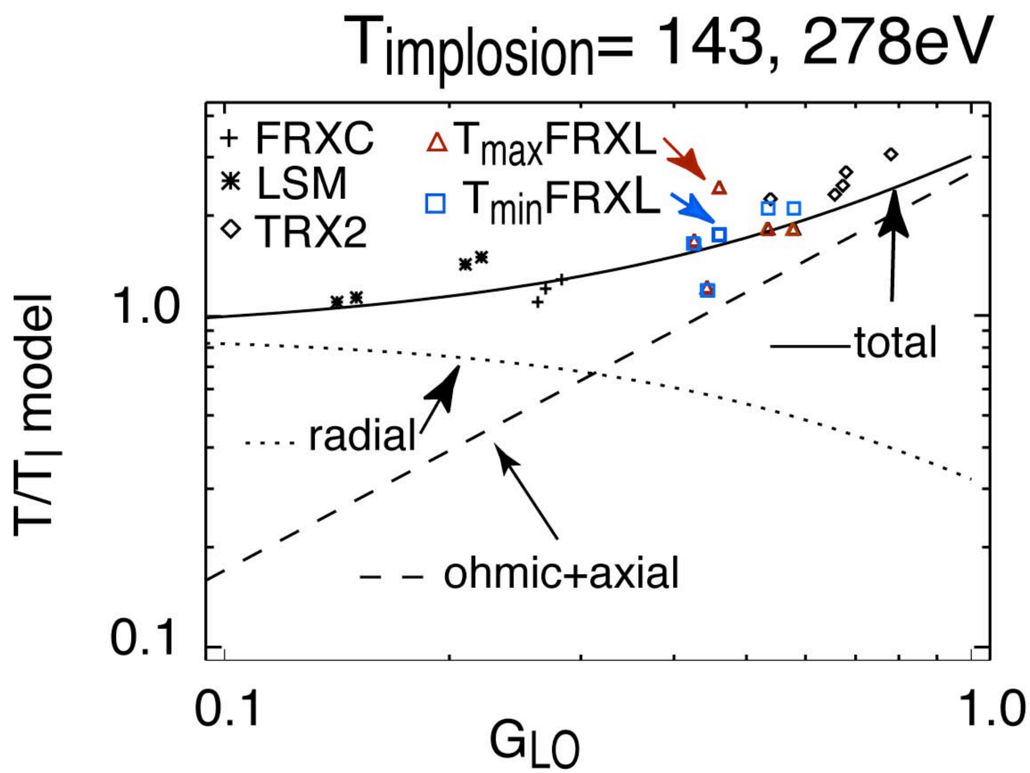
flux retention fraction: other FRC's & model



f_Φ for high density FRC fits conventional scaling

Enhance ohmic over radial shock heating



- $\langle T_e + T_i \rangle / T_{impl}$ vs $G_{LO} = \Phi_{LO} / \Phi_{GN}$
- G_{LO} = lift off / Green Newton flux
- Main bank field modulation affects nominal implosion temperature T_{impl}

Large G_{LO} => dissipate trapped flux

=> ohmically heat high density FRC

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Summary physics

- FRX-L is on-line, exploring a wide operating parameter space; translation experiments up next.
- Flux confinement and annihilation is both a practical and physics issue. We rely on flux annihilation to heat the FRC plasma, characterized by resistivity $\eta_\perp$*
- FRX-L operates at the extremum of collisionality compared with other FRC experiments.
- Data shows that
  – FRX-L profiles are approximately rigid rotor like shape, but β gradients tend to be less than model.
  – Resistivity $\eta_\perp$* ≈ 2x rigid rotor predictions, but anomalous (10-20x) classical coulomb resistivity

Summary program

- MTF pulsed approach to fusion is very different from mainstream and most ICC scenarios
- Several collaborators investigate physics & engineering
- Improved high density FRX-L target plasmas scale with conventional FRC wisdom
- 2004: New diagnostics, design FRX-L translation exp'ts, growing theory support
- Four year plan => physics demonstration of MTF FRC implosions Shiva Star, Kirtland AFRL

Other MTF related presentations

At CT2004

• Zhang	FRXL data details
• Ryutov	plasma liners
• Slough	PHD pulsed high density FRC

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